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PRESSURE DISTRIBUTION OVER THE WINGS OF AN MB-3 AIRPLANE IN FLIGHT

By F. H. NORTON

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1924

AERONAUTICAL SYMBOLS.

1. FUNDAMENTAL AND DERIVED UNITS.

	Symbol.	Metric.		English.	
		Unit.	Symbol.	Unit.	Symbol.
Length	l	meter	m.	foot (or mile)	ft. (or mi.).
Time	t	second	sec.	second (or hour)	sec. (or hr.).
Force	F	weight of one kilogram	kg.	weight of one pound	lb.
Power	P	kg.m/sec		horsepower	HP
Speed		m/sec	m. p. s.	mi/hr	M. P. H.

2. GENERAL SYMBOLS, ETC.

Weight, $W=mg$.

Standard acceleration of gravity, $g=9.806\text{m/sec.}^2=32.172\text{ft/sec.}^2$

Mass, $m=\frac{W}{g}$

Density (mass per unit volume), ρ

Standard density of dry air, 0.1247 (kg.-m.-sec.) at 15.6°C. and 760 mm. = 0.00237 (lb.-ft.-sec.)

Specific weight of "standard" air, 1.223 kg/m.^{3} = 0.07635 lb/ft.^{3}

Moment of inertia, mk^2 (indicate axis of the radius of gyration, k, by proper subscript).

Area, S; wing area, S_w, etc.

Gap, G

Span, b; chord length, c.

Aspect ratio = b/c

Distance from $c.\ g.$ to elevator hinge, f.

Coefficient of viscosity, μ.

3. AERODYNAMICAL SYMBOLS.

True airspeed, V

Dynamic (or impact) pressure, $q=\frac{1}{2}\rho V^2$

Lift, L; absolute coefficient $C_L=\frac{L}{qS}$

Drag, D; absolute coefficient $C_D=\frac{D}{qS}$.

Cross-wind force, C; absolute coefficient $C_C=\frac{C}{qS}$.

Resultant force, R

(Note that these coefficients are twice as large as the old coefficients L_c, D_c.)

Angle of setting of wings (relative to thrust line), i_w

Angle of stabilizer setting with reference to thrust line i_t

Dihedral angle, γ

Reynolds Number $=\rho\frac{Vl}{\mu}$, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi/hr., normal pressure, 0°C: 255,000 and at 15.6°C, 230,000;

or for a model of 10 cm. chord, 40 m/sec., corresponding numbers are 299,000 and 270,000.

Center of pressure coefficient (ratio of distance of C. P. from leading edge to chord length), C_p.

Angle of stabilizer setting with reference to lower wing. $(i_t-i_w)=\beta$

Angle of attack, α

Angle of downwash, ϵ

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BY

By F. H. NORTON
Massachusetts Institute of Technology

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REPORT No. 193.

PRESSURE DISTRIBUTION OVER THE WINGS OF AN MB-3 AIRPLANE IN FLIGHT.

By F. H. Norton.

SUMMARY.

This investigation was carried out to determine the distribution of load over the wings of a high speed airplane under all conditions of flight. In particular it was desired to find the pressure distribution, during level flight, over the portions of the wings in the slipstream and, during violent maneuvers, over the entire wing surface. The research was conducted at Langley Field by the National Advisory Committee for Aeronautics at the request of and with funds provided by the Army Air Service.

The method used, similar to that described in N. A. C. A. Report No. 148, consisted in connecting a number of holes in the surface of the wings to recording multiple manometers mounted in the fuselage of the airplane. In this way simultaneous records could be taken on all of the holes for any desired length of time.

The results obtained in this investigation may be briefly summarized as follows:

1. There occur in the slipstream, in level flight, positive values of lift of 100 lb/sq. ft. at the leading edge of the upper wing and negative values of over 60 lb. / sq. ft. on the leading edge of the lower right wing and the trailing edge of the lower left wing. Approximately 80 per cent of the load at any point is due to reduction of pressure on the upper side, tending to pull the fabric away from the supporting frame.

2. The values of lift on the ailerons and wing tips in a sharp aileron roll are only slightly greater than in steady flight.

3. The lift given by the wings when suddenly flattened out of a dive is about 80 per cent of the total dynamic load on the airplane, the fuselage and tail carrying the remainder. The lift per sq. ft. on the upper and lower wings under these conditions is in the ratio of 4 to 3

4. The center of pressure coefficient on the upper wings remains under all conditions at about 0.30. On the lower wing it varies between 0.53 and 0.32.

5. The distribution of lift along the span (moments taken about center line) is substantially equivalent to a uniform distribution under all conditions.

INTRODUCTION.

As far as is known, there has previously been no attempt made to measure completely the distribution of pressure over the surface of wings, in either steady or accelerated flight, probably on account of the experimental difficulties inherent in this type of test. The only work that seems to have been done on wing pressure distribution in flight is the measurement by the British of the distribution along a single rib in steady flight.

Attention is called to the large amount of information that can be obtained from a pressure distribution test that requires not more than a few minutes to record. The total lift of the wings, its exact distribution, the center of pressure movement, and the aileron load are determined directly, while the load on the body and tail can be computed from the preceding data. The accuracy is fully as great as needed by the designer. While the instrumental instal-

lation required for such work is extensive, it is fully justified by the volume and precision of the results obtained.

As the information obtained from this test is rather extensive, it has been condensed for convenience into Table III.

The designer should know what the loads on the wings of an airplane will be, under the most severe conditions of flight, for the determination of the stresses in the fabric, in the ribs, and in the spars. The necessity for this information was newly emphasized quite recently by troubles encountered with a number of high speed airplanes in which the fabric was stripped from the under surface of the wings, where it would naturally be expected that a pressure, rather than a suction, existed.

The following accidents in particular show the need for complete information on the distribution of lift over the wings of high speed airplanes:

1. While flying just before the Deutsch Cup Race in 1921, de Romanet, in a Lumiere de Monge monoplane, lost the fabric of one wing by ripping. The airplane spun and dived to the ground, killing the pilot. The fabric was the same as on the Spad, which was never known to rip unless shot to pieces.

2. In the same race Sadi Lecointe's accident on the Nieuport monoplane is reported to have been caused by the fabric's bursting.

3. The retirement of James in the Bamel was a consequence of loosened fabric on the *bottom* surface of the portion of the top wing in the slipstream.

4. The death of Lieutenant Neidermyer at McCook Field in 1922 was probably the indirect result of stripping of wing covering, during a roll, of the Fokker pursuit airplane he was flying.

5. Many instances were reported during the war, where airplanes in combat lost their wing fabric.

It has been uncertain whether or not the wings of an airplane in accelerated flight, when lifting three or four times their normal load, had the same center of pressure position as for an equal angle of attack at equilibrium speeds and whether the distribution of load along the span in accelerated flight was the same as when the wings carried a normal load. Also there has been practically no information available on the lift encountered by the ailerons and wing tips in accelerated flight, and the designer has been working rather blindly in so far as these loads are concerned.

In the present test the distribution of pressure over the wings was examined in steady flight at various airspeeds and engine speeds, and particular care was taken to determine the lift in the slipstream on both the right and left side. Further, the distribution of pressure was measured when the airplane was being maneuvered violently, when dynamic loadings of considerable magnitude were produced. Finally, the lift on the wing tips and ailerons was studied when the lateral control was used sharply.

The principal references to the distribution of pressure over wings are given below:

(1) Pressure Distribution over Fixed Aerofoils—Model Test. N. A. C. A. Report No. 150, 1922.

(2) Distribution of Load over Wing Tips and Ailerons. N. A. C. A. Report No. 161, 1922.

(3) Investigation of the Distribution of Pressure over the Entire Surface of an Aerofoil, R. & M. No. 73, 1913.

(4) Pressure Distribution on Model F. E. 9 Wings, R. & M. No. 347, 1917.

(5) Pressure Distribution on the Wings of a Biplane of R. F. A. 15 Section and with Raked Tips. R. & M. No. 353, 1917.

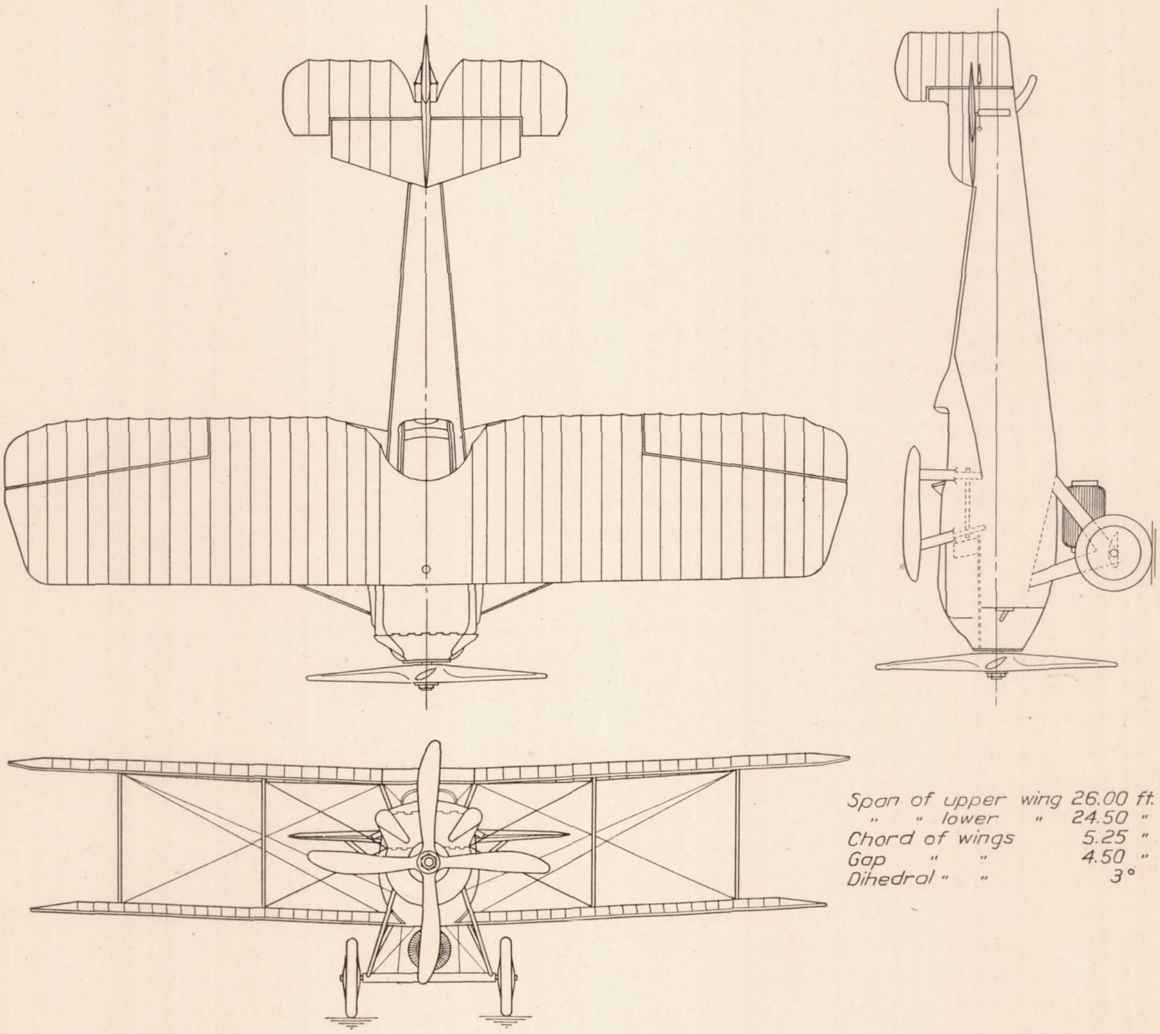
(6) Distribution of Pressure on the Upper and Lower Wings of a Biplane. R. & M. No. 355, 1917.

(7) Pressure Distribution on Wings with Fixed Balanced Ailerons. R. & M. No. 709, 1920.

AIRPLANE.

As it was desired to use in this investigation an airplane having a high maximum speed, a new MB-3 pursuit airplane was borrowed by the National Advisory Committee for Aeronautics from the Army Air Service. In many ways this airplane was especially suitable for these

tests as it was high powered and had a good performance; on the other hand, vibration during flight had been observed to be considerable and numerous instances had indicated that this type was structurally weak. The characteristics of the airplane are given in Table I below:



Views of rebuilt MB-3 pursuit airplane

TABLE I.

CHARACTERISTICS OF MB-3 USED IN TESTS.

Span of upper wing	26.0 ft.	Horizontal tail surface area	23.0 sq. ft.
Span of lower wing	24.5 ft.	Area of ailerons (both)	22.0 sq. ft.
Chord of wings	5.25 ft.	Stabilizer setting with propeller axis	0°.
Gap of wings	4.50 ft.	Propeller diameter (four blades)	7.54 ft.
Stagger of wings	None.	Propeller pitch (approximate)	7.8 ft.
Dihedral of wings	3°.	Weight of airplane during tests	2,320 lb.
c. g. position on chord	32.5%	Weight per HP. (330 at 1,825 R. P. M.)	7.2 lb.
c. g. position vertically	On thrust line.	Rated horsepower (1,825 R. P.M.)	330 HP.
Distance of *c. g.* from elevator hinge	12.3 ft.	Maximum horizontal speed (0.9 standard density)	150 M. P. H.
Area of upper wing	123.8 sq. ft.	Minimum horizontal speed (0.9 standard density)	55 M. P. H.
Area of lower wing	108.2 sq. ft.	Maximum rate of climb (0.9 standard density)	1,400 ft./min.
Area of both wings	232.0 sq. ft.	Weight per sq. ft. of wing area	10.0 lb.

The wing section is shown in Figure 1 together with the R. A. F. 15 section for comparison. It is very interesting to note the great divergence between the actual section turned out by the constructor and the R. A. F. 15 section which was supposed to be used. The change was

probably made after the original design was laid out to accommodate deeper spars, but instead of adopting a thick, but still efficient section, the upper surface of the R. A. F. 15 was simply bulged out over the spars. The resulting section undoubtedly gives a high-speed performance distinctly inferior to that of the R. A. F. 15.

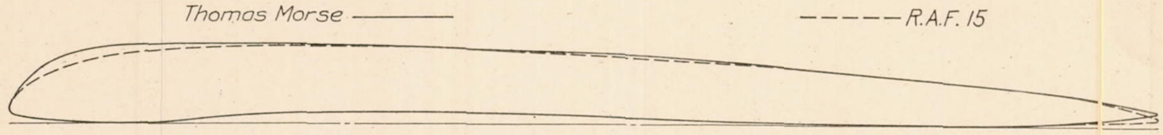


FIG. 1.—Comparison of the Thomas Morse section with the R. A. F. 15

It was considered desirable to make a number of changes in the standard airplane, first from the point of view of safety, and second to facilitate the test. The more important are enumerated below:

1. The radiator and the fuel tank were removed from the center section, which was made to conform with the wing section. This was done in order to prevent disturbance of the air flow in this section of the upper wing, to provide greater visibility for the pilot, and to permit loading the manometers with film conveniently.

2. A 180 HP. Lamblin radiator was placed just over the axle and was found to give very satisfactory cooling.

3. The rear center section bulkhead was changed so that it aligned with the rear center section strut, both to allow more room for placing the multiple manometers and to give greater strength and rigidity to the center section.

4. A number of heavy ribs were put in both the upper and lower wings, as several wing failures on this type of airplane indicated insufficient strength here.

5. When the wings were re-covered, the stitching was closely placed to prevent the fabric's stripping.

6. Heavier interplane struts were installed to prevent lateral deflection.

7. A number of fittings were replaced by ones of heavier metal and the engine section was stiffened.

8. The tip of the balance on the elevator was removed to prevent hunting of the longitudinal controls.

9. The rudder post was stiffened to prevent vibration.

10. All of the military equipment was removed to make room for the instruments.

11. A four-bladed propeller, which was put on the airplane, somewhat reduced the vibration.

Such extensive changes, of course, took a considerable length of time, but it was felt that they were justified because the nature of the present test demanded very violent maneuvering and the instruments installed required a minimum of vibration. The pilot reported that the airplane as rebuilt could be handled easily and was a decided improvement over the original model. A photograph of the rebuilt airplane is shown in Figure 2.

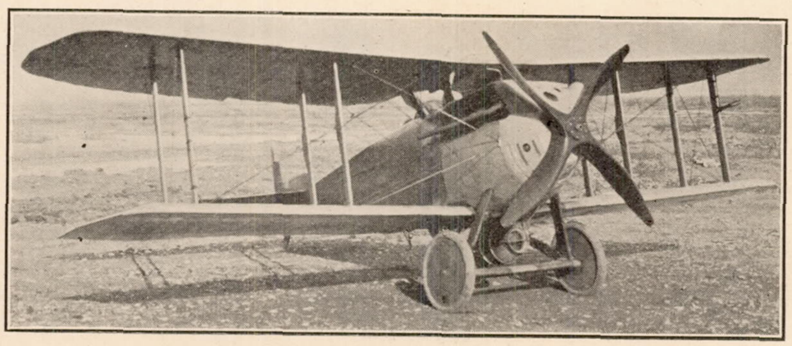


FIG. 2.—The rebuilt MB-3 pursuit airplane

For some reason unknown to the writer this airplane was designed to have a 3° increase in incidence of the upper wing for the inner bays, giving a considerable positive decalage with the lower wing and washout to the tips of the upper one. It is very improbable that this could increase the longitudinal stability as there is no stagger. It does, however, markedly increase the lift of the upper wing, especially around the center at small angles of attack, and it also probably increases the aileron effectiveness and makes spinning difficult. It would have been desirable to have repeated part of the tests on this airplane when rerigged to a constant angle of incidence for both wings. However, the structural changes in carrying this out would have been so extensive that it was not considered advisable, for it was felt that results of more value could be obtained by later repeating the tests on another type of airplane which was already rigged with uniform incidence. The actual angle of incidence of the wings in relation to the propeller axis is plotted in Figure 3.

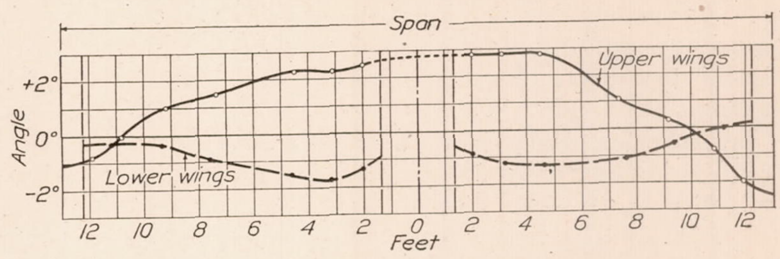


FIG. 3.—The actual angles of incidence relative to the propeller shaft

INSTRUMENTS.

The method used in applying the holes to the surface of the wing was the same as that described in N. A. C. A. Report No. 149. A small section of wing before covering is shown in Figure 4 where the tubes and openings are plainly evident. This method gave holes flush with the surface and allowed them to move with the fabric. In all cases they were quite free from leaks.

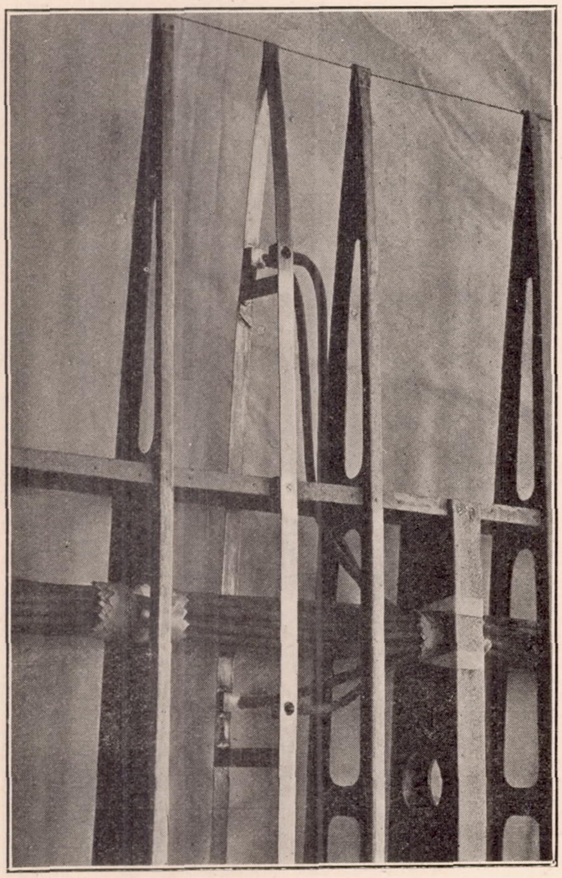


FIG. 4.—A portion of the MB-3 wing skeleton, showing tubes and surface connections for pressure distribution tests

A plan of the wings giving the location of all of the holes is shown in Figure 5. In most of the tests the upper and lower holes at each point on the wing were connected to the opposite sides of a single manometer capsule. In this way 120 holes could be accommodated at once. However, as the manometers did not allow the use of all the holes simultaneously, the steady flight runs were made in two parts, the first with the manometers connected to all of the holes in the slipstream and the second with the manometers connected to a few of the slipstream holes and all of the holes on the outer portion of the wing. In the runs with accelerated flight the latter method of connection was used entirely, as it was thought that the close inspection of the slipstream region under this condition was not of interest. As will be noted from the plan of the wings, an exploration of the pressure was made on the right upper wing tip and the left lower wing tip. This was done since it seemed quite legitimate to assume symmetrical conditions outside of the slipstream, as the angle of incidence was closely symmetrical.

In addition to the measurements of pressure differences between the upper and lower wing

surfaces, the pressure differences between the interior of the wing and the upper and lower surfaces were determined for a few positions. This was done by running four static tubes from the interior of each wing to small reservoirs in the cockpit. Each surface hole was then connected directly to one side of a capsule and the corresponding reservoir connected to the other side.

The manometer used in this test has been described fully in N. A. C. A. Report No. 148 and consists essentially of 30 diaphragm capsules, all recording photographically on a single film. In this test it was necessary to use two of the instruments and they were installed immediately in front of the pilot, in the space usually occupied by the machine guns, as shown in Figure 6. The separate capsules were adjusted for different sensitivities, as the holes on the leading edge of the wing had pressures going as high as 200 lb./sq. ft. while the pressures at the holes in the middle and rear of the wing did not exceed 40 or 50 lb./sq. ft. The instruments could be loaded with daylight loading film drums, although the available space was very limited.

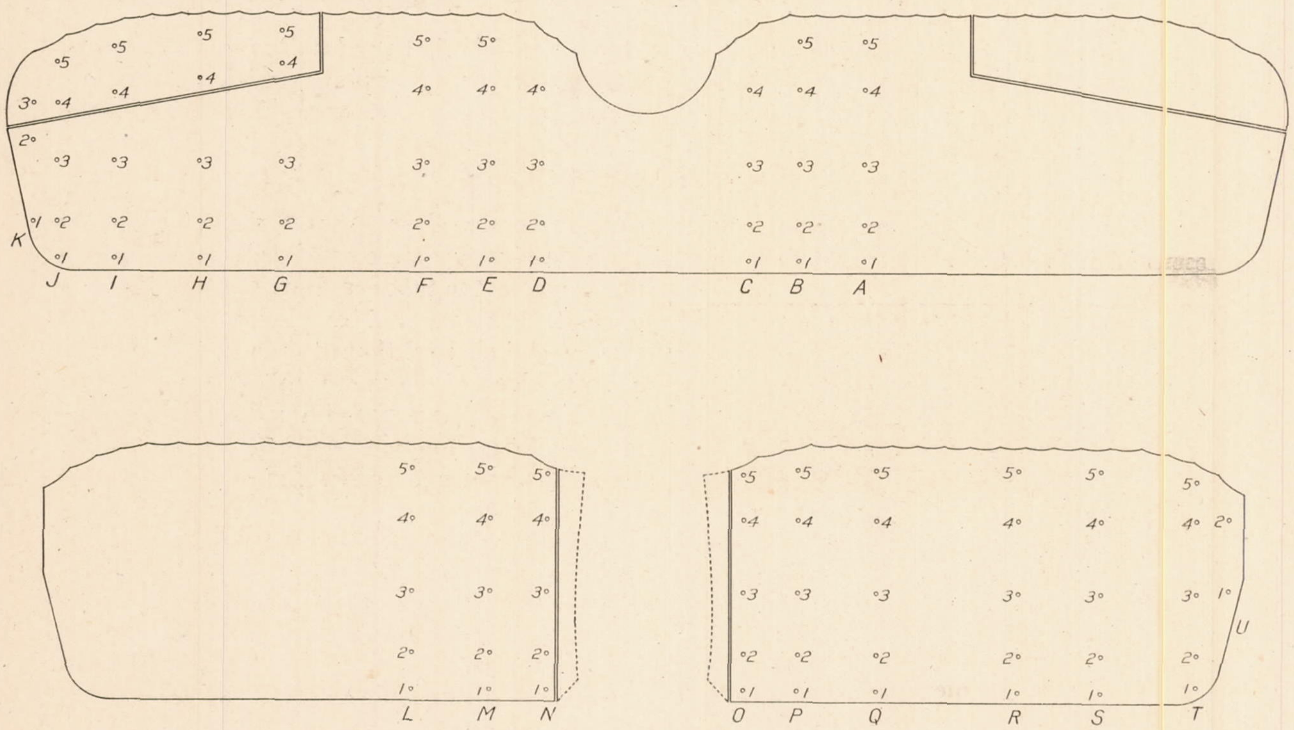


FIG. 5.—Plan of wings showing location of pressure holes

An accelerometer was used in all of the flights where there was accelerated motion. The instrument was the N. A. C. A. single component accelerometer described in N. A. C. A. Report No. 148 and it was mounted at the center of gravity of the airplane to prevent errors from angular motions.

The positions of all three controls were recorded by the control position recorder described in N. A. C. A. Report No. 148.

A check on the pilot's flying was obtained by the N. A. C. A. recording airspeed meter described in N. A. C. A. Technical Note No. 64. The airspeed meter was connected to a swiveling Pitot static head mounted on a boom extended forward from the right outer strut.

All the instruments were synchronized by means of the electric chronometer described in N. A. C. A. Technical Note No. 117.

SCOPE OF TESTS.

The pressure difference between upper and lower surfaces was measured at every pair of holes for speeds of 70, 115, and 145 M. P. H. at closed, medium, and full throttle under steady conditions. It is thought necessary, however, to show here only the 70 M. P. H. runs at 1,000

and 1,600 R. P. M. and the 145 M. P. H. runs at 1,300 and 1,900 R. P. M. The pressure difference between the interior of the wing and the outer surface was measured for a number of the holes, those in the slipstream giving the higher readings.

The pressure difference was measured on every pair of holes outside of the slipstream and on one row of holes in the slipstream when the airplane was: (*a*) Rolled sharply, with the ailerons, to the right and to the left; (*b*) suddenly flattened out of dives at 115 and 140 M. P. H., in order to give a large angle of attack to the wing; and (*c*) pulled around quickly in a vertically banked turn at 150 M. P. H., to obtain high dynamic load.

It would have been of considerable interest from a theoretical point of view if the distribution of pressure could have been taken during a spin. As the actual loading during a steady spin is not large, the omission is unimportant from a structural point of view.

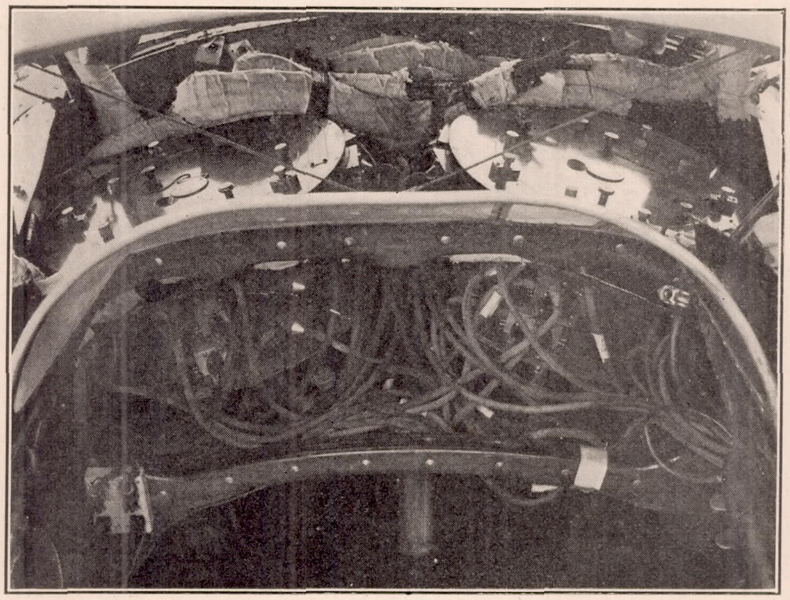


FIG. 6.—Installation of recording multiple manometer

PRECISION.

The multiple manometer was calibrated before and after the test and showed no appreciable change. Each separate capsule had its calibration curve, so that the deflection of the light beam could be measured directly from the film record and the pressure in lb./sq. ft. taken off the curve. The pressures as read are in all cases precise to ± 5 lb./sq. ft., but for the smaller pressures the error is probably not more than ± 1 lb./sq. ft. It should be noted that the purpose of this test was the measurement of the large pressures encountered in accelerated flight, and therefore the instruments were not adjusted to measure accurately the fine variations in pressure over the wings in steady flight.

The error due to lag in the tubes between the manometer and the opening of the wing has been fully discussed in N. A. C. A. Report No. 148, and, as the tubes here did not exceed 15 feet in length, it is clear that no error greater than 2 per cent of the pressure measured would be encountered.

The openings in the surface of the wings were very satisfactory and no leaks of any kind occurred here. A considerable amount of difficulty, however, was encountered because a certain species of wasp found these holes of just the right dimensions for nests. A few leaks due to porosity were found at first in some of the rubber tubes, but this was corrected by pumping rubber cement through the tubes and then blowing it out with air. Every tube and connec-

tion was carefully gone over before the test to be sure that no leaks or stoppages of any kind existed.

The greatest part of the probable error in the determination of total pressure on the wings is due to lack of information as to pressure at points between adjacent holes. The error from this cause may amount to 5 per cent. In all cases the areas of constant pressure contours were integrated as accurately as the precision of the data warranted.

The center of pressure coefficient in these tests is precise to 0.01, as evidenced by the excellent check between runs at the same speed. This precision is considerably better than was initially expected.

Nearly all of the steady flight runs were repeated and the agreement was excellent in all cases, showing that the flying was carefully executed.

The accelerations were recorded with a precision of ± 0.1 g. The airspeed head was not calibrated, as previous tests showed that a swiveling head gave practically a correct reading without an installation correction at all but the lowest speeds. The recording airspeed meter was carefully calibrated in the laboratory before the test, so that the readings given here should be correct to within ± 3 M. P. H. No density correction was made to the airspeed reading, as all flights were made at 0.9 standard density. The control positions were recorded to the nearest 0.5°, and the R. P. M. of the engine is precise to ± 20 R. P. M.

RESULTS OF TESTS.

The distribution of lift over the wings for the various conditions of flight is shown, in Figures 7–13, by means of contour charts. This method of plotting was selected as being most satisfactory in showing clearly the graduations in pressure. All of the curves are drawn through the experimental points.

The distribution of lift along the span, obtained by integrating the loads on each rib, is shown for all cases in Figure 14. The areas under these curves give the total lift on the surfaces. The moment of the lift about the center line on one-half the wing, divided by that lift, gives the lateral position of the center of pressure.

The fore and aft *C. P.* coefficient, as found by integration along each rib, is plotted similarly in Figure 15. The weighted mean ordinates of these curves give the mean *C. P.* coefficient for the wing.

The individual pressures on the upper and lower surfaces, measured by determining the pressure on one surface and subtracting from the difference between both surfaces, are given in Table II. The position of the holes can be ascertained by referring to Figure 5.

The lift in the slipstream during steady flight is large and irregular on this airplane, ranging from +100 lb./sq. ft. on the leading edge of the upper wing to −60 lb./sq. ft. on the leading edge of the lower right wing, both occurring at high airspeeds and engine speeds. It was also noted that at low airspeeds and high engine speeds—that is, while climbing—a negative lift of 70 lb./sq. ft. occurs at the trailing edge of the lower left wing, close to the body. The down loads are due in part to the low angle of attack of the lower wing and in part to the rotation of the slipstream, although the effect of the latter is smaller than would be expected. The negative lift on the lower wing may be quite serious, as the lower surface of the wing is not usually constructed to withstand great suction.

The greatest suction on the upper surface, measured in reference to the pressures inside of the wing, was, in steady flight, 76 lb./sq. ft. This amounted to 84 per cent of the total lift at that point. All of the high suctions measured were about this percentage of the total load at the points measured. The greatest pressure measured at any point on the lower surface was 24 lb./sq. ft., but most of the pressures, as can be seen from Table II, are much smaller than this. The greatest suction on the lower surface, compared to the pressure inside of the wings, was found to be 43 lb./sq. ft.

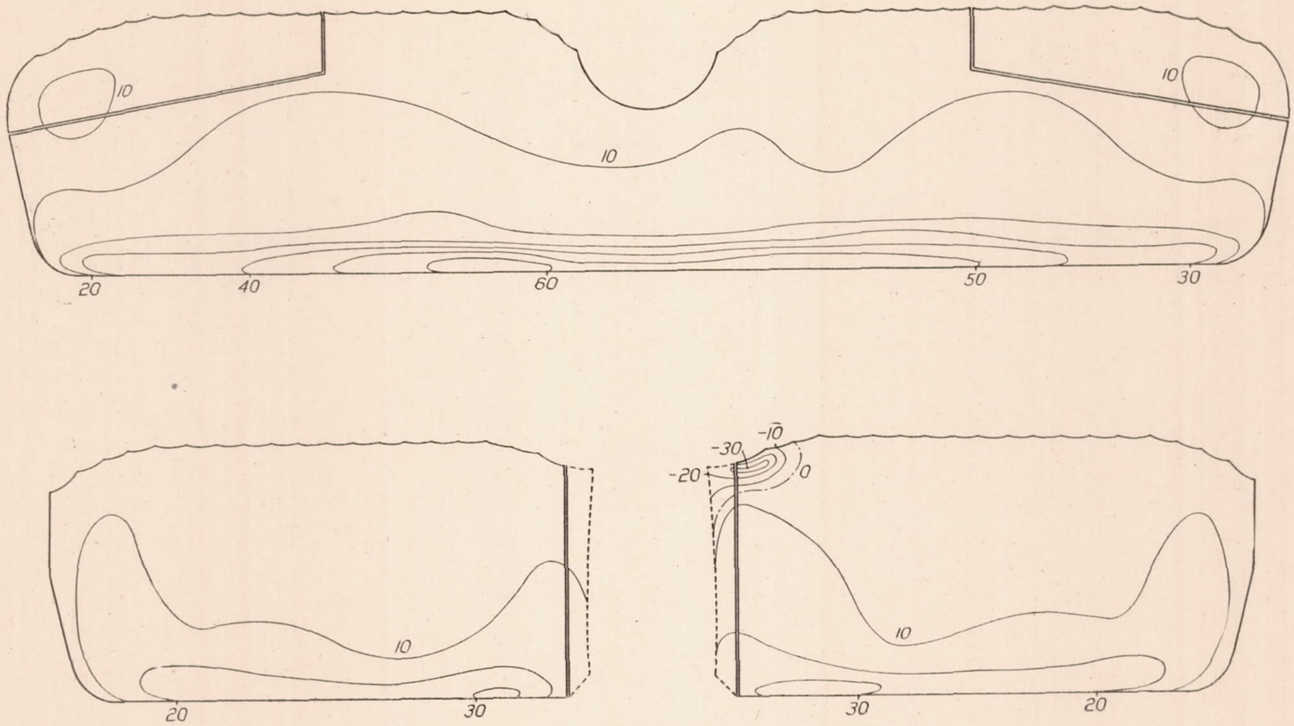


FIG. 7.—Lift of wings in steady flight at 70 M. P. H. and 1,000 R. P. M.

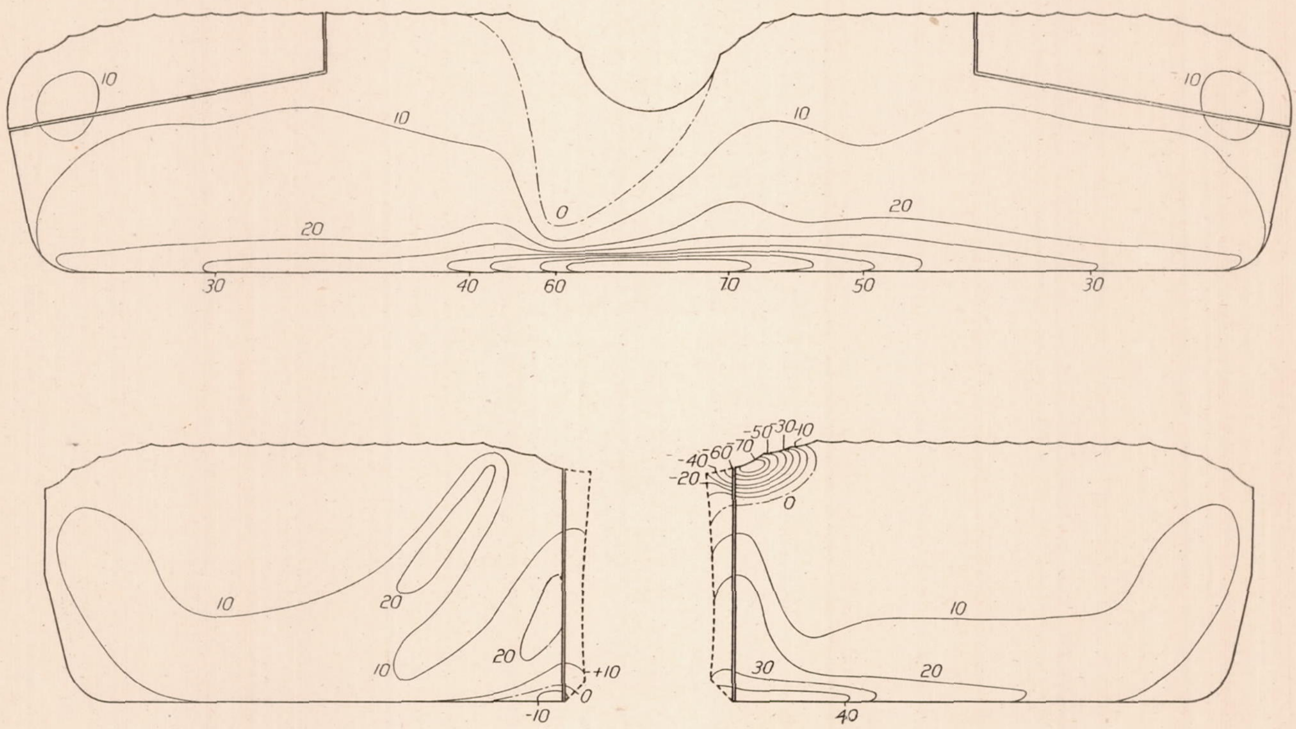


FIG. 8.—Lift of wings in steady flight at 70 M. P. H. and 1,600 R. P. M.

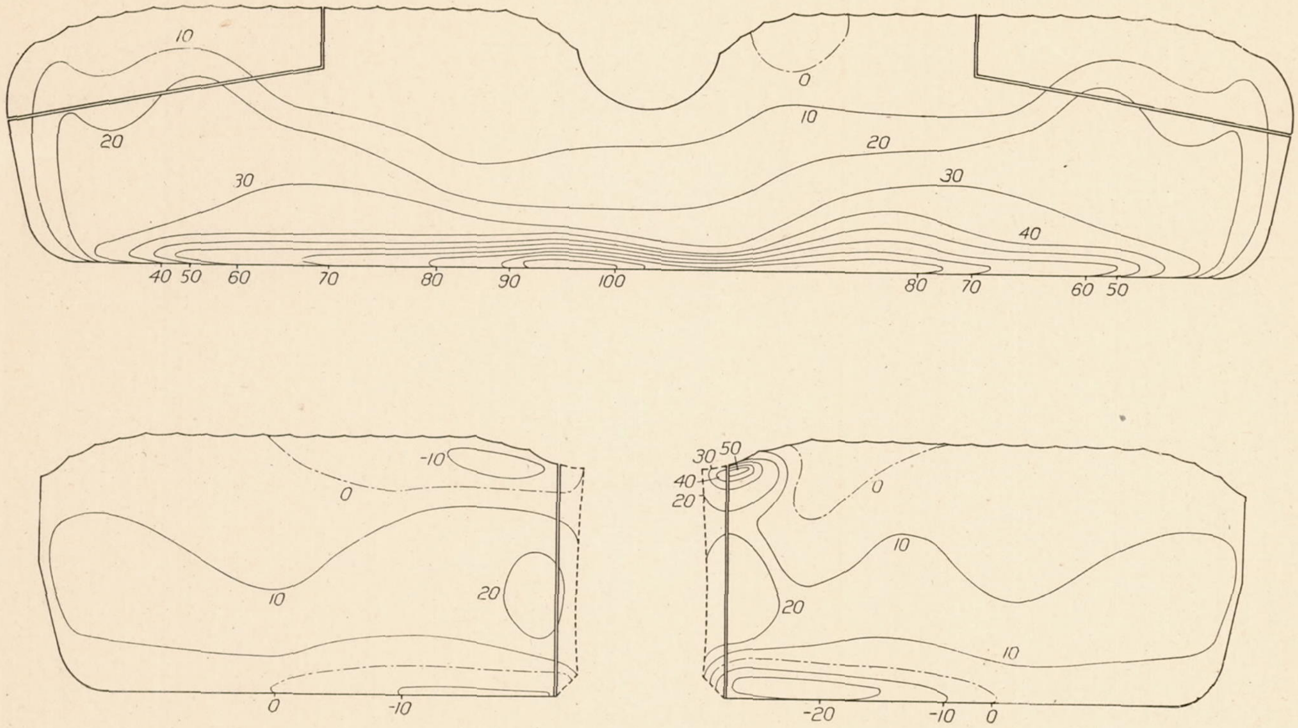


FIG. 9.—Lift of wings in steady flight at 145 M. P. H. and 1,300 R. P. M.

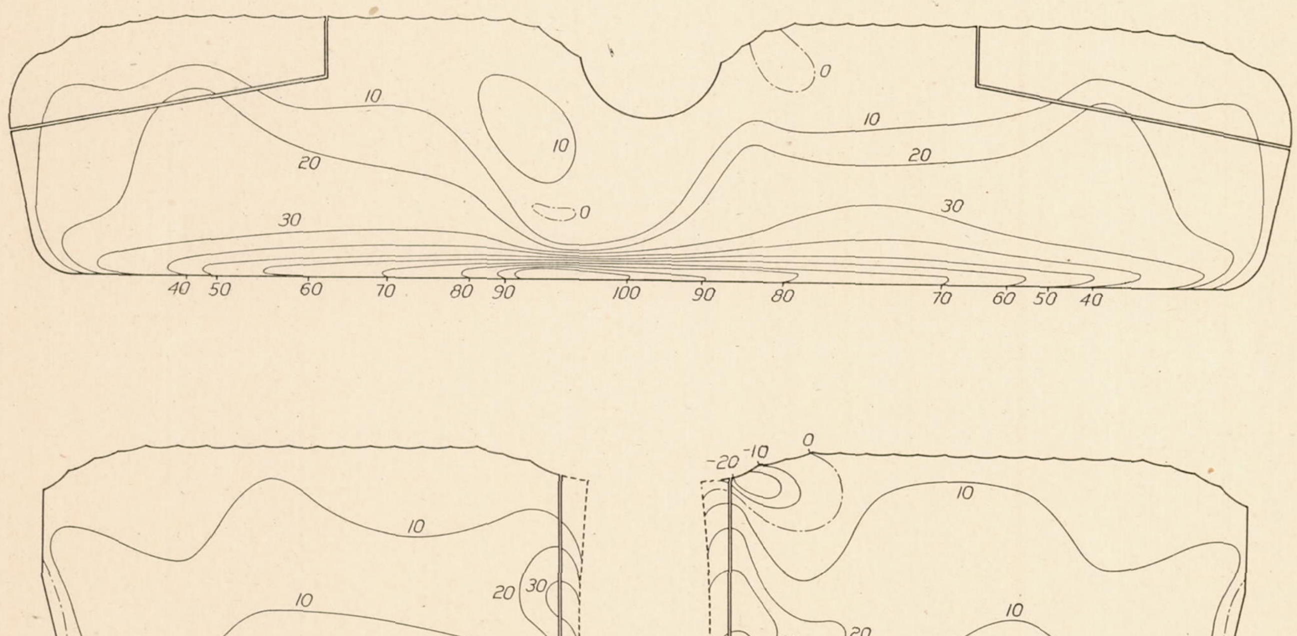


FIG. 10.—Lift of wings in steady flight at 145 M. P. H. and 1,900 R. P. M.

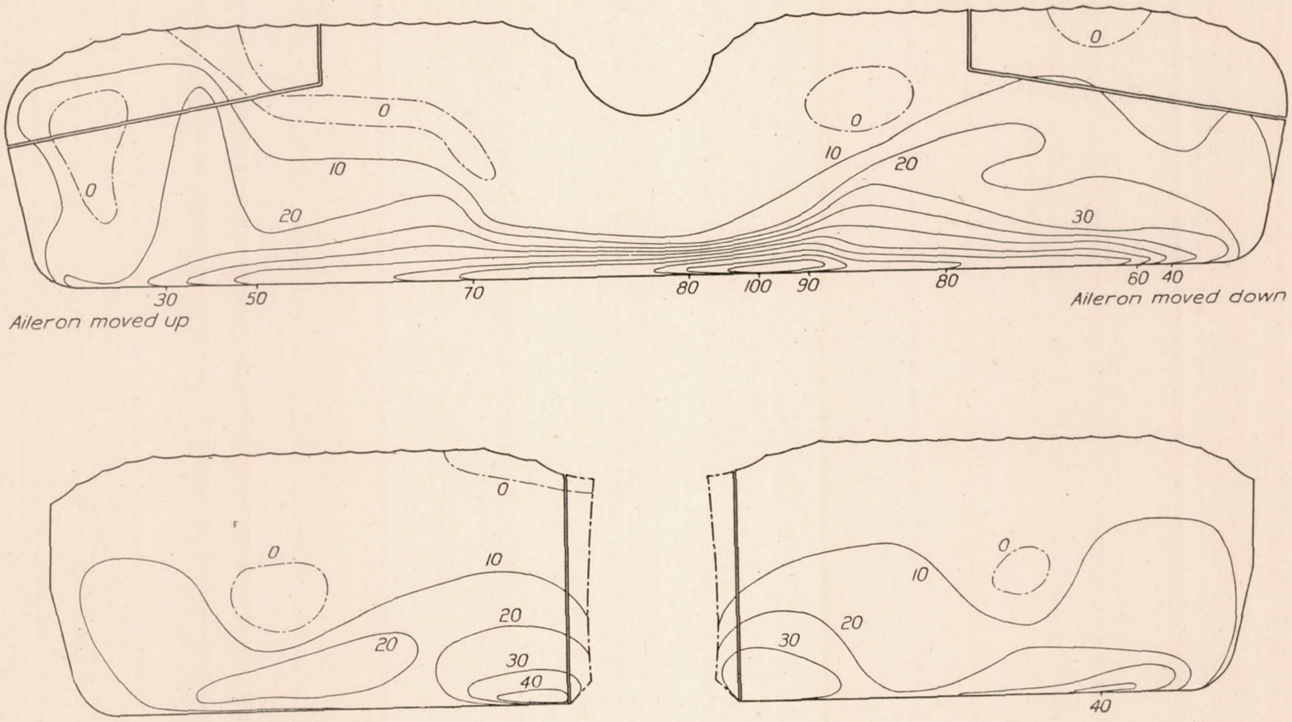


FIG. 11.—Lift of wings in a right aileron roll at 138 M. P. H. Ailerons moved suddenly. (Lifts indicated are maximum values and do not occur simultaneously as in other flights.)

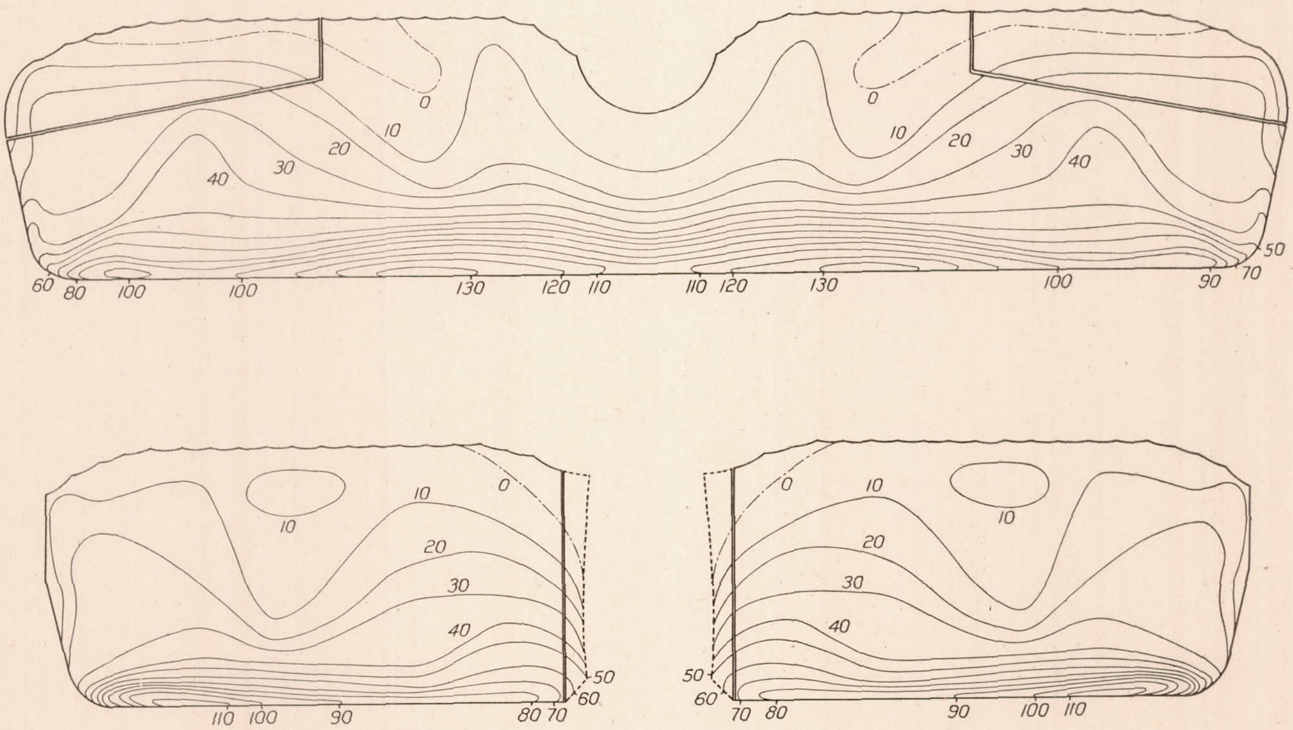


FIG. 12.—Lift of wings in a sudden flattening out of a dive at 140 M. P. H. and 1,900 R. P. M. Acceleration, 3.6 g.; elevator pulled up suddenly 10°

The lift of the wings and ailerons, due to an aileron roll, was found to be practically no greater than in steady flight, as can be seen from the contour chart representing this condition. Such a statement may, if hastily considered, be surprising but viewed in the light of what is known of loads on stabilizers, it will be seen to be reasonable. Therefore it appears that an aileron load can never be anything but small. In N. A. C. A. Report No. 153 there is computed from experimental data the aileron forces required to produce an aileron roll when the ailerons are turned to 13°, suddenly, at an airspeed of 80 M. P. H. which corresponds to the same angle of attack as the higher speed of the MB-3. It was found here that the maximum aileron moment about the center of gravity was 7,000 lb. ft. We may assume that on the MB-3 the lateral radius of gyration and the damping about the X axis will have approximately the same relation to the span as

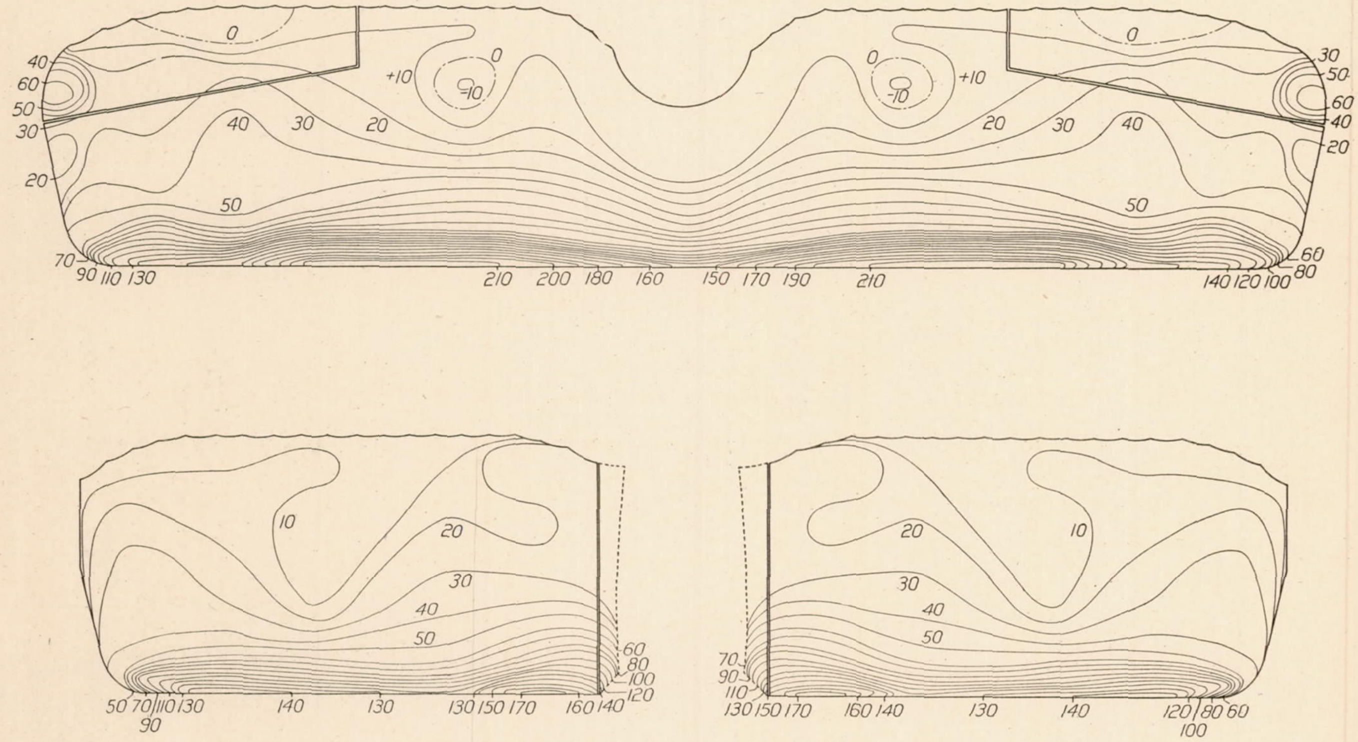


FIG. 13.—Lift of wings in a vertical bank at 150 M. P. H. and 1,900 R. P. M. Acceleration, 4.2 g.; elevator pulled up 12°

they have on the JN-4h. Thus the lift on the ailerons and wing tips will be about 200 lb. on each side, or, as this is distributed over an area of about 30 square feet, 6 lb./sq. ft.

A marked peak of pressure was observed on the tip of the ailerons and, during longitudinal maneuvers, this peak rose in height to over 60 lb./sq. ft. This lift is almost identical with that found on positive raked wings in the wind tunnel and emphasizes the fact that the positive raked wing gives an excessive lift on the rear spar and the ailerons and decreases the ease and effectiveness of the lateral control.

Where the angle of attack is large, as in flattening out of a dive, the wings support only 80 per cent of the total load on the airplane, the remainder being carried partly by the propeller, spreader board, and tail, but mainly by the fuselage. This airplane has a relatively large body area compared with the wing area so that this percentage would be somewhat increased in other types of airplanes.

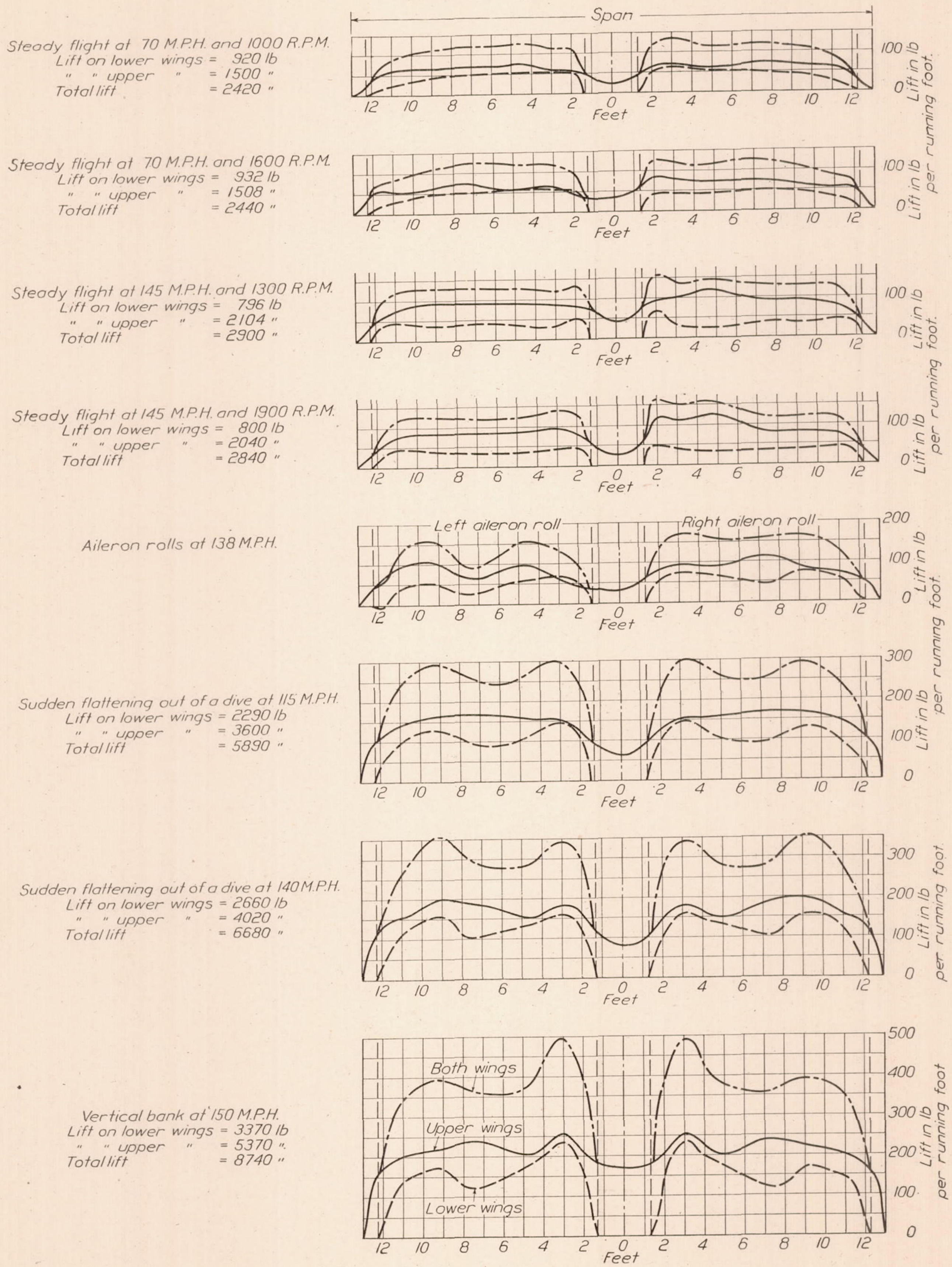


FIG. 14.—Integrated lift of wings

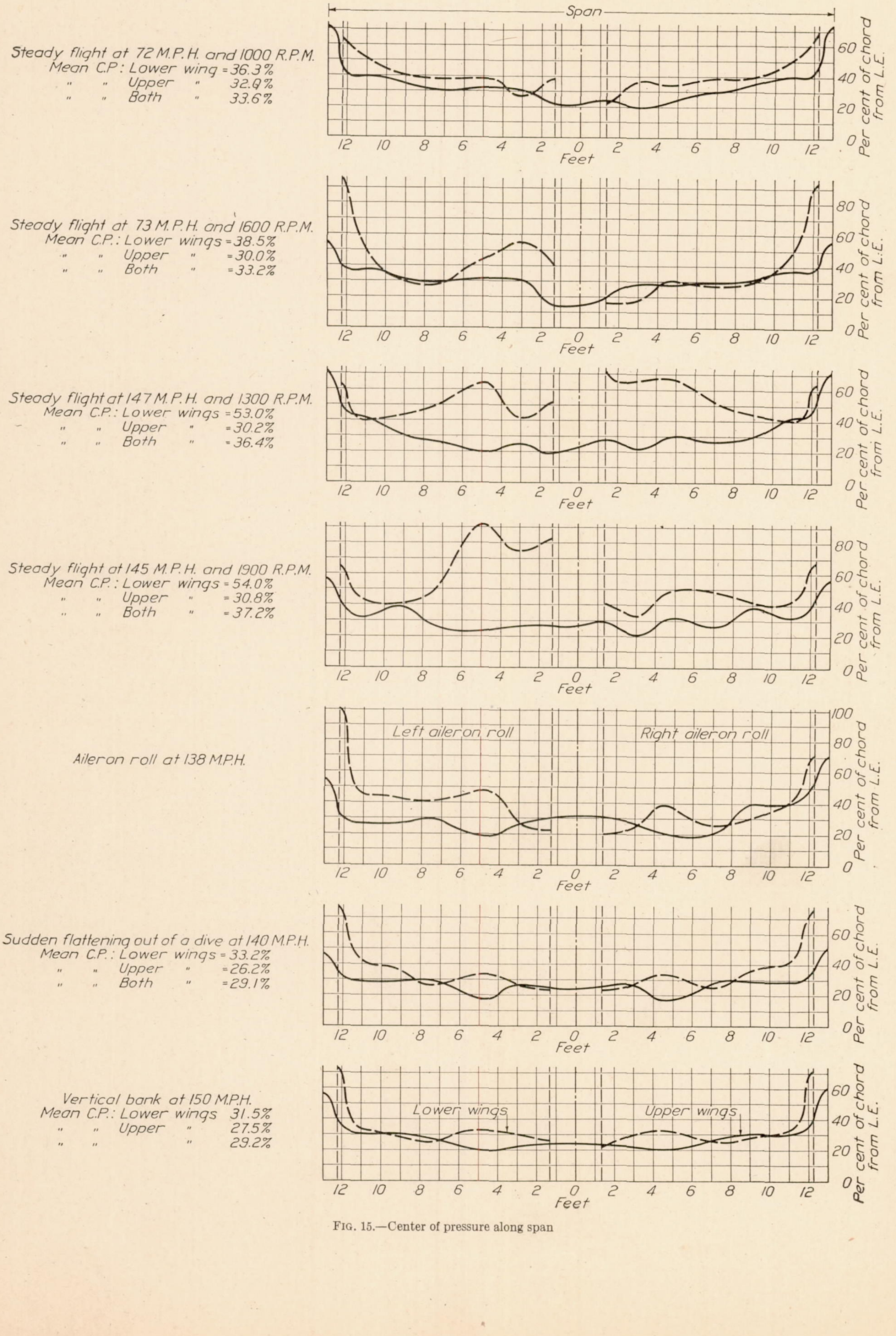


FIG. 15.—Center of pressure along span

In a vertically banked turn at 150 M. P. H., where the dynamic load rose to 4.2 g, the wings carried 90 per cent of the total load, the larger percentage being due to the smaller angle of attack in this maneuver.

In steady flight at 145 M. P. H. the lift per square foot of the upper wing is twice that on the lower. The total lift of the wings is about 400 pounds greater than the weight of the airplane, due to the down load on the fuselage and tail. The negative lift of the fuselage is very large and may considerably decrease the efficiency of this airplane at high speeds.

At 70 M. P. H. the lift per square foot of the upper wing is 50 per cent greater than on the lower one and the total lift of the wings is approximately equal to the weight of the airplane, the small difference observed being well within the experimental error, although approximately the same difference was observed on all of the runs at this speed.

In longitudinal maneuvers, such as suddenly flattening out of a dive at 115 and 140 M. P. H. and turning sharply at 150 M. P. H. the average lifts of the wings in lb./sq. ft. were, respectively, 25, 29, and 37, and the lifts of the upper and lower wings were approximately in the ratio of 4 to 3.

The center of pressure coefficient on the upper wings in steady flight remains constantly at 0.31, but under high loading goes forward to 0.27. On the lower wing the *C. P.* coefficient changes from 0.54 at 145 M. P. H. to 0.37 at 70 M. P. H. and then to 0.32 under high dynamic load. The combined *C. P.* coefficient changes from 0.37 to 0.34 in steady flight from 145 to 70 M. P. H. and goes forward to 0.29 at high loadings. It is very interesting to note the almost stationary position of the center of pressure on the upper wing in ordinary flying conditions. This is due in part to the greater angle of incidence of this wing but can not be altogether accounted for in this way. On the other hand, while the lower wing has a lower loading under most conditions it has a considerably greater center of pressure travel which may account for some of the structural failures which have occurred in the lower wing of this airplane. It may be noted from Figure 15 that the center of pressure moves toward the trailing edge at the wing tip, which confirms the conclusion reached in wind tunnel tests.

The tail load, computed from the dynamic weight of the airplane and the distance between the center of gravity and the center of pressure, while disregarding the pitching moment of the fuselage (the thrust line passes through the *c. g.*), reaches a maximum value of only 5 lb./sq. ft. which agrees excellently with the information obtained in N. A. C. A. Report No. 148. This confirms the statement made there that the tail loads on an airplane are dependent mainly upon the center of gravity position and that dynamic loadings on the airplane are practically independent of the airplane speed.

The lift on the vertically projected area of the fuselage in lb./sq. ft. is approximately -10 in steady flight at high speeds and as high as $+37$ when suddenly flattening out of a dive at 140 M. P. H. This loading seems very high but at high angles of attack the fuselage lift is probably increased by virtue of its interference with the wings and tail surface.

The distance of the lateral center of pressure on the upper wing, expressed as a fraction of the half span, is 0.48 in steady flight and 0.51 during longitudinal maneuvers. On the lower wing it is 0.55 in steady flight and 0.54 in longitudinal maneuvers. If moments are taken about the center line of the fuselage the distribution of lift may be assumed practically uniform under all conditions. It should be noted here that the upper wing has a considerable washout at the tip which would tend to relieve the loading on the tip of the wing, especially at high speed. An airplane having uniform incidence along the span might have even more severe conditions of lift distribution than shown here, although at high angles of attack the difference between the two cases would probably be negligible.

CONCLUSIONS.

As this test was made on one airplane it is a little unwise to draw general conclusions from the results obtained. However, the following facts seem to stand out clearly and should be carefully considered in new designs:

1. The construction of the wing surface in the slipstream should be made very strong and especial care should be taken to secure the surfaces from pulling off due to suction. While the upper surface of the wing has in the past generally been strong enough from this point of view, the lower surface at the leading edge and trailing edge should be stiffened.

2. On the airplanes of the high-speed type where the wings are working at angles of attack as low as 0° it would be well to set the incidence of the wings in respect to the body at such an angle that the lift of the fuselage would be zero or slightly positive at the same time that its drag is a minimum. This may quite appreciably increase the high-speed performance.

3. Everything approaching a positive rake on the wing tip, or horizontal tail surface, is in every way disadvantageous both to the distribution of lift on the wing tip and to the lateral control. Wing tips having approximately a 30° negative rake and well-rounded corners seem to give the best results.

4. The lift on and due to the ailerons in lateral maneuvers is not as great as the lift caused by longitudinal maneuvers, so that stresses due to the former condition need not be seriously considered.

5. In computing the stresses in the wing the designed load factor of the airplane (that is, the factor by which the normal weight of the airplane is multiplied to obtain the maximum dynamic loading) may be reduced by 10 per cent due to the fact that the wings are not supporting the entire load during longitudinal maneuvers.

6. It is seen that the practice of setting decalage between the upper and lower wing as was done in the MB-3 is of no advantage structurally, as it does not materially increase the load on the upper wing at very high angles of attack and it does increase the center of pressure travel materially on the lower wing.

7. It would seem that a careful investigation of fuselage shapes to develop a construction having a large lift coefficient at high angles of attack would be advisable in view of the large load taken by the fuselage in longitudinal maneuvering.

TABLE II.

SEPARATE PRESSURES ON UPPER AND LOWER SURFACES.

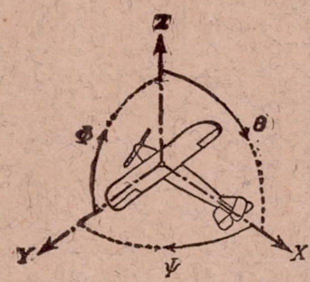
Hole No.	Conditions of flight and point of pressure measurement.											
	145 M. P. H.—1,900 R. P. M.			145 M. P. H.—1,300 R. P. M.			70 M. P. H.—1,600 R. P. M.			70 M. P. H.—1,000 R. P. M.		
	Upper surface and interior of wing.	Lower surface and interior of wing.	Upper surface and lower surface.	Upper surface and interior of wing.	Lower surface and interior of wing.	Upper surface and lower surface.	Upper surface and interior of wing.	Lower surface and interior of wing.	Upper surface and lower surface.	Upper surface and interior of wing.	Lower surface and interior of wing.	Upper surface and lower surface.
A-1	55	13	68	56	24	80	34	11	45	38	12	50
B-1	62	8	70	66	9	75	38	19	57	38	12	50
B-2	20	14	34	20	10	30	12	8	20	10	9	19
C-1	62	12	80	50	10	60	42	20	62	30	18	48
C-2	19	11	30	19	1	20	14	8	21	11	6	17
D-1	76	14	90	77	13	90	44	6	50	38	12	50
E-1	54	16	70	70	8	78	33	12	45	38	17	55
E-2	21	3	24	17	11	28	8	12	20	5	10	15
F-1	50	15	65	72	0	72	29	4	33	40	5	45
F-2	15	17	32	26	1	27	10	2	12	10	15	25
Q-1	−4	−18	−22	−2	−14	−16	14	11	25	14	11	25
Q-2	0	10	10	0	5	5	0	12	12	0	11	11
P-1	17	−34	−17	4	−24	−20	27	11	38	17	13	30
P-2	20	3	23	14	−3	11	11	1	12	11	5	16
O-1	21	−43	−22	5	−25	−20	37	1	38	16	13	29
O-2	18	4	22	14	1	15	16	10	26	8	12	20
N-1	−19	−34	−53	−10	−30	−20	−1	−9	−8	15	5	20
N-2	18	−6	12	14	2	16	12	4	18	9	6	15
M-1	−7	−33	−40	−8	−20	−12	10	4	14	23	5	28
M-2	0	5	5	5	5	10	7	7	14	7	9	16
L-1	−8	−18	−26	0	−15	−15	7	7	14	17	5	22
L-2	0	0	0	0	7	7	0	0	0	0	8	8
Value of q'	....	54	....	....	54	....	....	13	....	....	13	....
Positive value	Suction	Pressure	Up load	Suction	Pressure	Up load	Suction	Pressure	Up load	Suction	Pressure	Up load

Pressure difference between upper surface and inside of wing is positive when the latter is higher.
Pressure difference between lower surface and inside of wing is positive when the latter is lower.
Pressure difference between lower surface and upper surface is positive when the latter is lower.
q' is calculated for airspeed of airplane and will be larger in slipstream.

TABLE III.

CONDENSED RESULTS OF TESTS ON MB-3.

	Conditions of flight						
	Steady flight.				Flattening out of dive.		Vertically banked turn.
Initial airspeed in M. P. H. (Indicated—P=.9 std.)	145	145	70	70	115	140	150
R. P. M. of propeller	1,900	1,300	1,600	1,000	1,700	1,900	1,900
Angle of attack (average) of upper wings	....	....	9.5°	9.5°	20°	18°	16°
Angle of attack (average) of lower wings	....	....	7.0°	7.0°	18°	16°	14°
Angle of attack (average) of both wings	....	....	8.3°	8.3°	19°	17°	15°
Lift of upper wings in pounds	2,000	2,100	1,500	1,500	3,600	4,000	5,300
Lift of lower wings in pounds	800	800	900	900	2,300	2,600	3,300
Lift of both wings in pounds	2,800	2,900	2,400	2,400	5,900	6,600	8,600
Lift of upper wings in lb./sq. ft	16.0	17.0	12.0	12.0	29.0	32.0	43.0
Lift of lower wings in lb./sq. ft	7.5	7.5	8.5	8.5	21.0	24.0	30.0
Lift of both wings in lb./sq. ft	12.0	12.5	10.5	10.5	25.0	29.0	37.0
Normal acceleration in terms of g (by accelerometer)	1.0	1.0	1.0	1.0	3.1	3.6	4.2
Total dynamic load on airplane in pounds (mass × acceleration)	2,320	2,320	2,320	2,320	7,200	8,400	9,700
Lift of horizontal tail surface in pounds	−50	−50	10	10	80	100	120
Lift of propeller due to fin effect in pounds	0	0	20	20	100	100	100
Lift of fuselage, spreader board, and radiator in pounds	−400	−500	−70	−70	1,100	1,600	900
C. P. coeffcient on upper wings	.31	.30	.30	.32	....	.26	.28
C. P. coefficient on lower wings	.54	.53	.39	.36	....	.33	.32
C. P. coefficient on both wings	.37	.36	.33	.34	....	.29	.29
Lift of the horizontal tail surface in lb./sq. ft	−2.0	−2.0	0.5	0.5	3.2	4.1	5.0
Lift of vertical project area of fuselage in lb./sq. ft	−10	−12	−2	−2	27	37	22
Lateral *C. P.* (fraction of one-half span):							
Upper right	.50	.48	.45	.48	....	.52	.50
Upper left	.49	.46	.50	.47	....	.52	.50
Lower right	.58	.53	.53	.47	....	.56	.52
Lower left	.62	.56	.52	.45	....	.56	.52
Both right	.52	.47	.48	.48	....	.54	.51
Both left	.53	.49	.51	.47	....	.54	.51
Average of all	.53	.48	.50	.48	....	.54	.51
Angular position of elevator when readings were taken	*Down.* 3°	*Down.* 3°	*Down.* 4°	*Down.* 4°	*Up.* 13°	*Up.* 7°	*Up.* 9°
Inclination of propeller axis to horizon	0°	6°	18°	0°	19°	17°	15°
Maximum possible dynamic loading at given speed in terms of (g)	....	....	....	....	4.4	6.4	7.4



Positive directions of axes and angles (forces and moments) are shown by arrows.

Axis.		Force (parallel to axis) symbol.	Moment about axis.			Angle.		Velocities.	
Designation.	Symbol.		Designation.	Symbol.	Positive direction.	Designation.	Symbol.	Linear (component along axis).	Angular.
Longitudinal	X	X	rolling	L	$Y \longrightarrow Z$	roll	Φ	u	p
Lateral	Y	Y	pitching	M	$Z \longrightarrow X$	pitch	Θ	v	q
Normal	Z	Z	yawing	N	$X \longrightarrow Y$	yaw	Ψ	w	r

Absolute coefficients of moment

$$C_l = \frac{L}{q\,b\,S} \quad C_m = \frac{M}{q\,c\,S} \quad C_n = \frac{N}{q\,f\,S}$$

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS.

Diameter, D
Pitch (a) Aerodynamic pitch, p_a
(b) Effective pitch, p_e
(c) Mean geometric pitch, p_g
(d) Virtual pitch, p_v
(e) Standard pitch, p_s
Pitch ratio, p/D
Inflow velocity, V'
Slipstream velocity, V_s

Thrust, T
Torque, Q
Power, P
(If "coefficients" are introduced all units used must be consistent.)
Efficiency $\eta = T\,V/P$
Revolutions per sec., n; per min., N
Effective helix angle $\Phi = \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS.

1 HP = 76.04 kg. m/sec. = 550 lb. ft/sec.
1 kg. m/sec. = 0.01315 HP
1 mi/hr. = 0.44704 m/sec.
1 m/sec. = 2.23693 mi/hr.

1 lb. = 0.45359 kg.
1 kg. = 2.20462 lb.
1 mi. = 1609.35 m. = 5280 ft.
1 m. = 3.28083 ft.